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Origins of the Kuroshio and Mindanao Current

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Award Number: N00014-10-1-0273
DURIP Award Number: N00014-11-1-0811
ESS Award Number: N00014-11-1-0429
http://chowder.ucsd.edu
http://spray.ucsd.edu

LONG-TERM GOALS

The boundary currents off the east coasts of the Philippines and Taiwan are of critical importance to the general circulation of the Pacific Ocean. The westward flowing North Equatorial Current (NEC) runs into the Philippine coast and bifurcates into the northward Kuroshio and the southward Mindanao Current (MC). Quantifying these flows and understanding their dynamics are essential to improving predictions of regional circulation, and to characterizing property transports that ultimately affect Pacific climate. Fluctuations in the Kuroshio and MC can significantly impact variability downstream. For example, the Kuroshio penetrates through Luzon Strait into the South China Sea and onto the East China Sea shelf. The Kuroshio front dramatically alters stratification and may impact internal wave propagation. OKMC incorporates observation, theory, and modeling to make fundamental advances in our knowledge of the origins of the Kuroshio and Mindanao Current.

OBJECTIVES

The overarching goal of OKMC is to quantify patterns of flow and fluxes of mass, heat, and salt, for the ultimate purpose of establishing predictability. We have three major research themes in OKMC:

- Transport and flow patterns
- Temperature/salinity properties and modifications

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Origins of the Kuroshio and Mindanao Current**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, San Diego,Scripps Institution of Oceanography,9500 Gilman Drive,San Diego,CA,92093**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Eddies and their effect on mean flow

This report covers contributions to these themes from several efforts at Scripps Institution of Oceanography. These efforts include the deployment of underwater gliders, drogued drifters, and profiling floats, and the use of forward and assimilative models. Specific objectives include:

- Establish the regional mean and variability of currents and water properties
- Identify fine-scale variability and its connection to regional properties
- Distinguish the effects of local and remote forcing on the origins of the Kuroshio and MC
- Provide targets for studies of predictability

APPROACH

The proposed observing system employs a suite of complementary platforms to meet the challenges posed by this vast, highly variable study area. Guided by previous studies and by directed analysis of historical data, long-endurance autonomous gliders are tasked to collect repeat occupations of key sections across the NEC, MC. Drifters and floats are used to illuminate the pathways by which the NEC ultimately forms the Kuroshio and MC. Numerical approaches aid interpretation and explore the predictive capabilities of regional models.

WORK COMPLETED

Gliders

Gliders are being used to observe the NEC and the Mindanao Current. Two Sprays are deployed from Palau every 4-5 months, one that proceeds northward across the NEC, and one that heads westward towards the MC. Operations commenced in June 2009 and have continued uninterrupted. The data set includes 18 glider missions, two of which are active at this time. To date, we have completed 19 crossings of the Mindanao Current, and 18 sections across the NEC (Figure 1). In total, the gliders have done over 11,000 dives, and covered over 49,000 km in 2800 days. The final recovery is scheduled for January 2014.

Analysis to date has focused on the NEC for two reasons. First, the NEC is more observationally tractable, as the glider is able to make relatively straight and repeatable sections. Second, and more importantly, the NEC provides the inflow condition for the region. Thus, many of the other components of OKMC focused on the Kuroshio benefit from knowledge of the NEC. The mean geostrophic velocity from the glider sections shows a clear pattern of westward flowing NEC in the upper ocean, with cores of eastward undercurrents below. The base of the NEC deepens to the north, in rough correspondence with the slope of potential density surfaces. Two cores of undercurrents are apparent at about 9.5°N and 13°N, each about 1.5° wide. These NEC undercurrents are a newly discovered feature, constituting one of the first fundamental results of OKMC (Qiu et al, 2013, GRL). The undercurrents are so strong that they force the depth-average flow in the upper 1000 m to vanish. So, the strongest net eastward flow in the upper 1000 m occurs not where the surface flow is strongest, but where the deep undercurrents are weakest, at about 11°N and 15°N. The NEC is gone by 17°N.

Mean salinity calculated from all sections shows two clear extrema associated with the prominent water masses in the region. A salinity maximum near 150 m (23.5 kg m^{-3}) runs down the center of the section in the NEC. This salinity extremum, sometimes called North Pacific Tropical Water (NPTW), is seen throughout the region, carried by all the major currents. Quantifying the path and evolution of NPTW provides a means to tie together OKMC measurements in different locations, and serves as a target for modeling and prediction. A salinity minimum exists near 500 m (26.5 kg m^{-3}) at the north end of the section. The salinity minimum, the well-known North Pacific Intermediate Water (NPIW), lies mostly beneath the major currents so it spreads relatively slowly. Glider profiles are separated by about 6 km, so they allow an examination of the submesoscale. This variance is largest on the isopycnals corresponding with salinity extrema, that is in the NPTW and NPIW water masses. The submesoscale variance is weakest in the region between the water masses. This pattern is quantified using wavelets to isolate variability at wavelengths shorter than 50 km. Variance calculated on isopycnals is clearly largest in the salinity extrema, implicating isopycnal stirring processes as the cause. A study of these layers as they exist in the Kuroshio was published in Oceanography magazine (Rudnick et al. 2011).

Analyses similar to those described for the NEC are beginning to be applied to the Mindanao Current sections. The interpretation is made challenging by the fact that the sections were not exactly repeatable because of strong currents. Comparable results are emerging, especially considering the evolution of the salinity extrema.

The use of gliders to observe high frequency internal waves has been investigated using data from previous deployments in the Luzon Strait region. The vertical velocity is deduced from fluctuations in the gliders' flight path. By averaging over several glider deployments over a year, the existence of internal waves traveling eastward into the Pacific from the Luzon Strait was ascertained. These waves had been predicted theoretically, but this was the first in situ observational evidence of their presence. A paper describing this work has been published in the Journal of Geophysical Research (Rudnick et al, 2013).

Graduate student Martha Schonau has joined our group supported by an Early Student Support (ESS) grant, and her doctoral research will focus on Spray glider data from OKMC.

Floats

Ten floats were deployed in August 2011 from the Japanese R/V Mirai. Data from these floats are processed through the Argo system, and are made available through GTS to modeling centers including NAVO. An additional 17 floats obtained through a DURIP were deployed in March 2013 from the R/V Mirai. Of the 27 floats deployed, all but one returned data. Analysis of these data is in collaboration with Bo Qiu of U. Hawaii, with the first publication addressing distinct cores of undercurrent beneath the NEC (Qiu et al., 2013).

Drifters

To enhance the historical near surface current data in the study area, deployments of surface drifters from the merchant vessels from Kaohsiung to eastern Australia were performed. The deployment locations were chosen from the analysis of the historical drifter dataset in order to sample the seasonal variability of the flow at the roots of the KC and of the MC. Professor Ruo-Shan Tseng at National Sun Yat-sen University was local contact point in Taiwan to store, prepare and deliver the drifters to the ship. The drifter deployments were completed in 2013. In total, we have deployed 268 SVP drifters (Figure 1) in the OKMC region from August 2010 through August 2013 (255 from VOS and 13 in Lamon Bay from the R/V Revelle).

The drifter data were first quality controlled and a kriging interpolation routine was then applied to obtain 6 hourly, regularly spaced, drifter location time series from which the drifters' velocities were obtained. A wind slip correction was also applied and the velocity data from drifters that had lost their drogue were recovered. The drifter data were analyzed using standardized techniques published in the peered reviewed literature to compute the Lagrangian statistics, the mean surface velocity field the eddy kinetic energy (EKE) and the unbiased geostrophic surface flow obtained from a combination of drifter, wind and satellite altimetry. Other dynamically important quantities such as the acceleration the drifters along their track, whose curl corresponds to the divergence of the mean and eddy vorticity fluxes, and the mechanical energy exchange between the mean flow and the eddies were also computed. Main results are as follows:

- the surface expression of the MC intensifies at the same location (~11N, 126,5E) throughout the year.
- the location at which the KC intensifies changes seasonally and, on average, is located at 17N 122.5E during the NE monsoon and shifts southward as far as 13.4.5N 124.5E during the SW monsoon.
- A well-defined surface connectivity between the MC and the NEC occurs year-round as shown by the large (1 m/s) speeds of drifters that from the NEC drift into the MC.
- The surface velocity of the KC also shows a well-defined seasonal cycle at 15.5N, 123.5 E, consistently with the seasonal changes, namely a wintertime increase, of the horizontal gradient of the sea level at the origin of the boundary current, as required by geostrophic adjustment.
- The decadal strengthening of the negative wind stress curl and trade winds in the subtropical area north of Hawaii and west of 150E are the driving forces of the decadal variability of a recently discovered wintertime westward current that occurs between 18N and 23N.
- The mechanical energy exchange between the mean flow and the eddies computed from the drifter data suggests a possible transfer of energy from the eddies to the mean flow in the KC and MC origin regions.

Modeling

The MITgcm 4D-Var state estimation using satellite SSH and SST with temperature and salinity profiles from floats and gliders is now being run systematically through the time of the experiment in two month segments. Each state estimate is tested by a forecast from the end of the hindcast period. This forecast is compared against the observations to look for skill against each of them. This tests the state estimate against independent observations. In the first few segments the forecast outperforms persistence some of the time. Because of the irregular sampling for both estimation and verification, an OSSE would be required to know whether the forecast could be expected to be good for any particular realization, but stable forecasts are seen as a good sign. The sensitivity calculations for the 1/6 degree regional domain are continuing, and are being checked for nonlinearity. The hypothesis is that the incoming influences propagate as linear waves south of about 18 N, and that information pathways are primarily linear near the bifurcation where the KC and MC are weak. This is being tested in forward and adjoint simulations. In addition, the correlation structure of the western boundary currents has been explored with the intent of creating a generalized transport index that could be used as a prediction (and sensitivity) target. Preliminary EOF results show correlation all along the Philippine coast, with correlated boundary current structure out to about 2 degrees offshore and to about 1000m depth. The model has also been explored for evidence of the subsurface countercurrents seen in the observations and in the POP and other models. They are present, but very weak, and are a possible target for sensitivity analysis and prediction.

A multi-decadal fine resolution (1/10°) global ocean general circulation model: the Parallel Ocean Program (POP), forced with synoptic interannually varying reanalysis atmospheric fluxes, was used to study the impact of remote and local forcing in the study region. The region, as well as being characterized by the entrant NEC and the emerging MC and KC, is impacted by westward propagating signals. To the south of about 20°N they are generally characterized as long-period, baroclinic Rossy waves, while to the north these signals are non-linear eddies (Chelton et al. 2007); the eddies largely form in the Subtropical Countercurrent (STCC) as a result of baroclinic instability. Mesoscale eddies in POP propagate into the study region in the 16°-26° N band east of Taiwan, the Luzon Strait, and the northern Philippines. Simulated eddy kinetic energy (EKE) at 15m in this band was found to be greatest in April through September and lowest in winter (January, February, March), in agreement with surface drifting buoy results. To understand the role of eddy forcing on the KC and MC we then calculated eddy vorticity flux convergences from daily averaged POP eddy momentum fluxes over the upper water column for 1994-2007, as well as for seasonal climatologies constructed for the same period. POP was also used to explore the mean and seasonal variability of the structure of the flow offshore of the Philippines in the NEC.

RESULTS

Our most important results are as follows:

- The mean NEC is firmly established, with the strongest flows in the south and near the surface. Eastward flowing undercurrents are robust features.
- Two clear salinity extrema defining the dominant water masses of the region are proving to be useful tracers connecting all currents in the region. These extrema are sites of enhanced submesoscale variability, indicating isopycnal stirring.
- The sensitivity of SSH and transport to wind stress curl spreads to the east going backwards in time, but advection is important. The influence of the model state on the gradients (nonlinearity) is more apparent at these shorter scales, and nonlinearity clearly increases poleward. The contribution of the coastal waveguide is smaller than that of the propagating Rossby waves, but it is still important, and points up the relation to island rule theory and its generalizations.
- Simulated eddy-mean flow interactions using POP showed eddy vorticity forcing to occur around the northern tip of the Philippines in the Luzon Strait, to the east of Taiwan, and to the south of the southern Philippines. Offshore of Taiwan results imply a northward acceleration of the mean poleward flowing KC by eddy forcing. Seasonal analyses show that the magnitude of this forcing varied such that the highest values occurred in spring and summer while the lowest occurred in fall, similar to the EKE variability to the east.
- POP also simulates deep permanent eastward flowing subsurface jets (~500-1000 m depth) at 9.5°N and 13°N along 134.5°E; core mean speeds are roughly 2 cms^{-1}. Climatological seasonal meridional sections of zonal velocity (Fig. 4) along 134.5°E show spatial variations: only one jet occurs in summer whereas two or three separate cores are seen in other seasons. The strongest speeds are seen in the winter.

IMPACT/APPLICATIONS

- The demonstration of glider utility in a strong western boundary current should influence future glider operations in similarly strong flows. Gliders have shown proven ability for the sustained observation of major ocean currents. All glider data is being sent to NAVO in real time.
- The value of drifters for regional oceanography is being further established through this program. All the drifter data were posted in real-time to the Global Telecommunication System of the World Weather Watch.
- The boundary current is found to be sensitive to local and basin-wide wind stress, providing a target for predictive models.

RELATED PROJECTS

Related projects include and ongoing Early Student Support grant and a completed DURIP. This project takes advantage of glider technology that has been developed through grants from several agencies including ONR, NSF, and NOAA.

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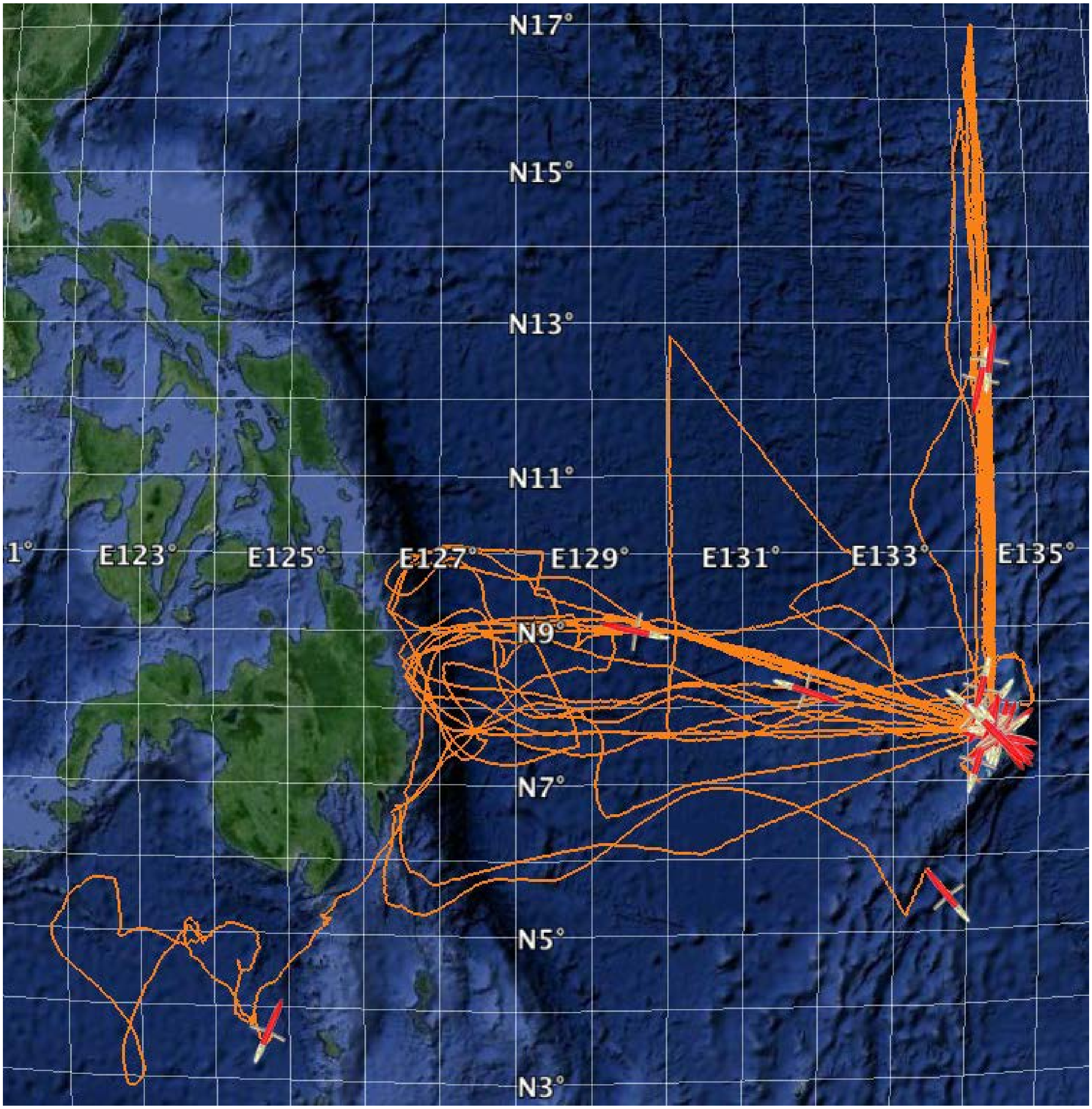

Figure 1. Spray glider trajectories for all missions since June 2009.

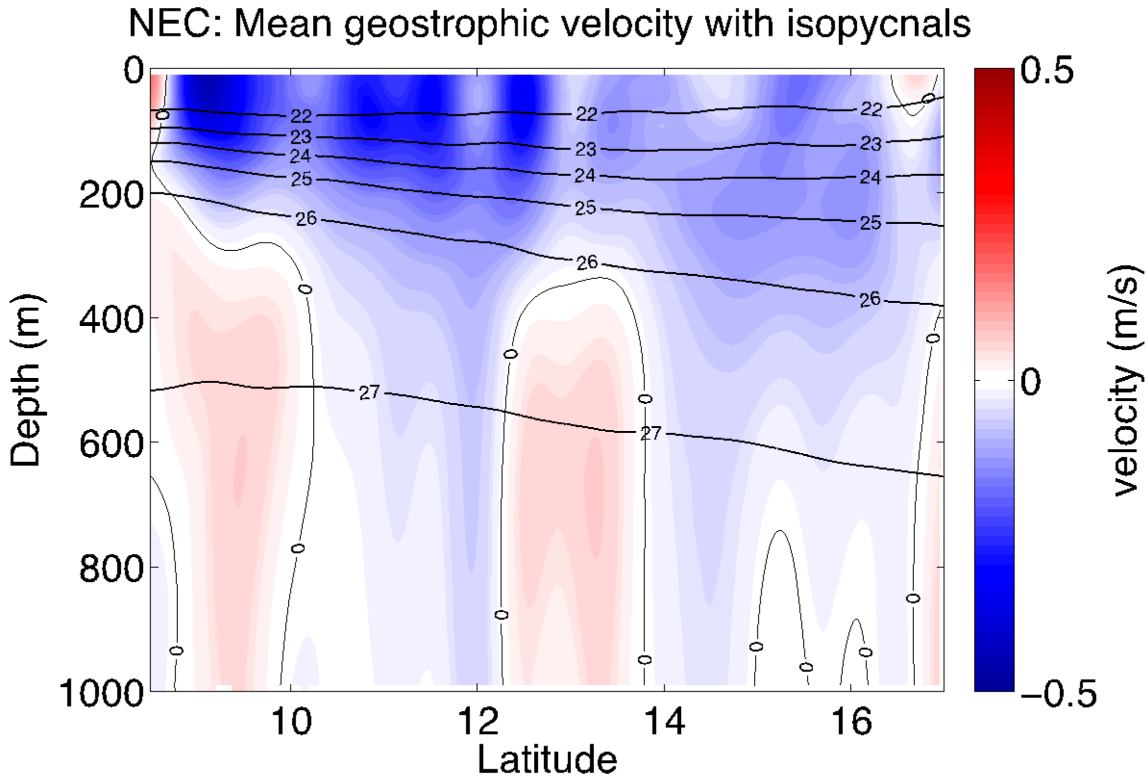

Figure 2. Mean eastward geostrophic velocity from glider sections across the NEC, along 134°20'E. The geostrophic flow is referenced to the depth-average current directly measured by gliders, revealing strong cores of eastward flow below the NEC.

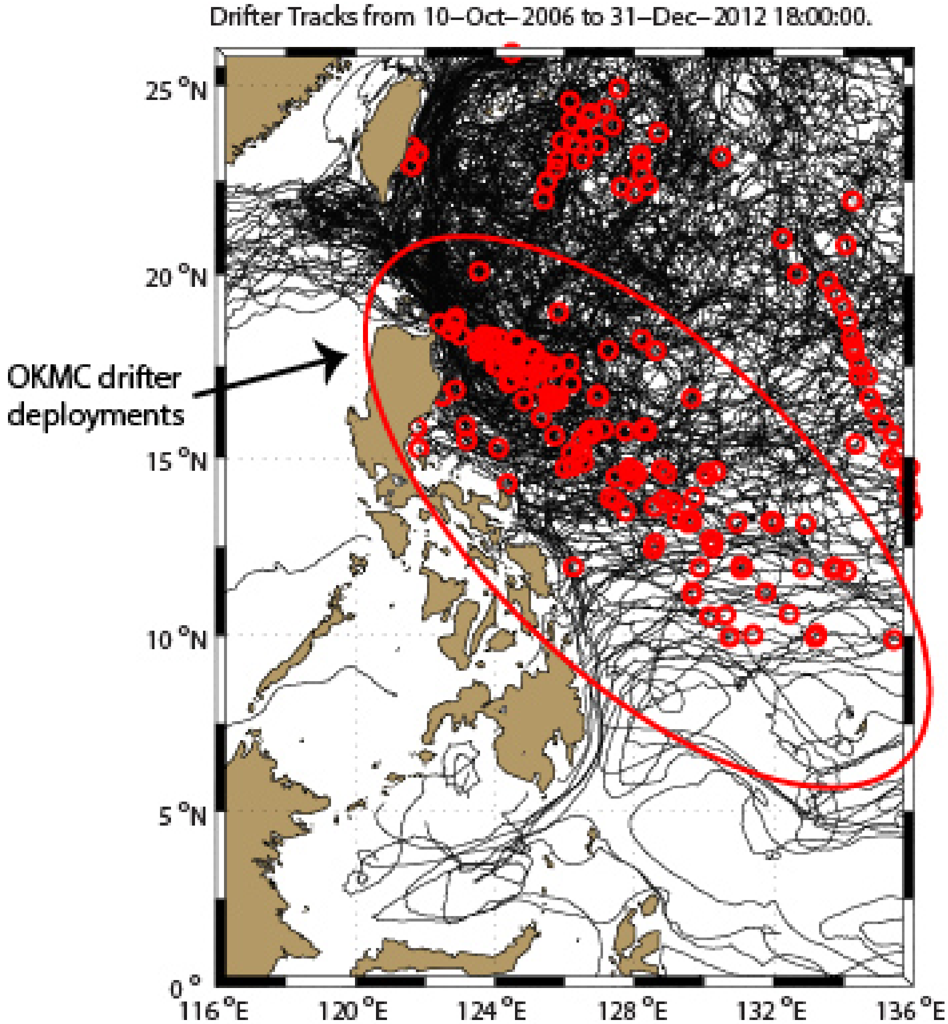

Figure 3. Drifter tracks in the NW Pacific Ocean during the OKMC period. The OKMC drifter deployments for the August 2010-December 2012 period are circled with the red ellipse.

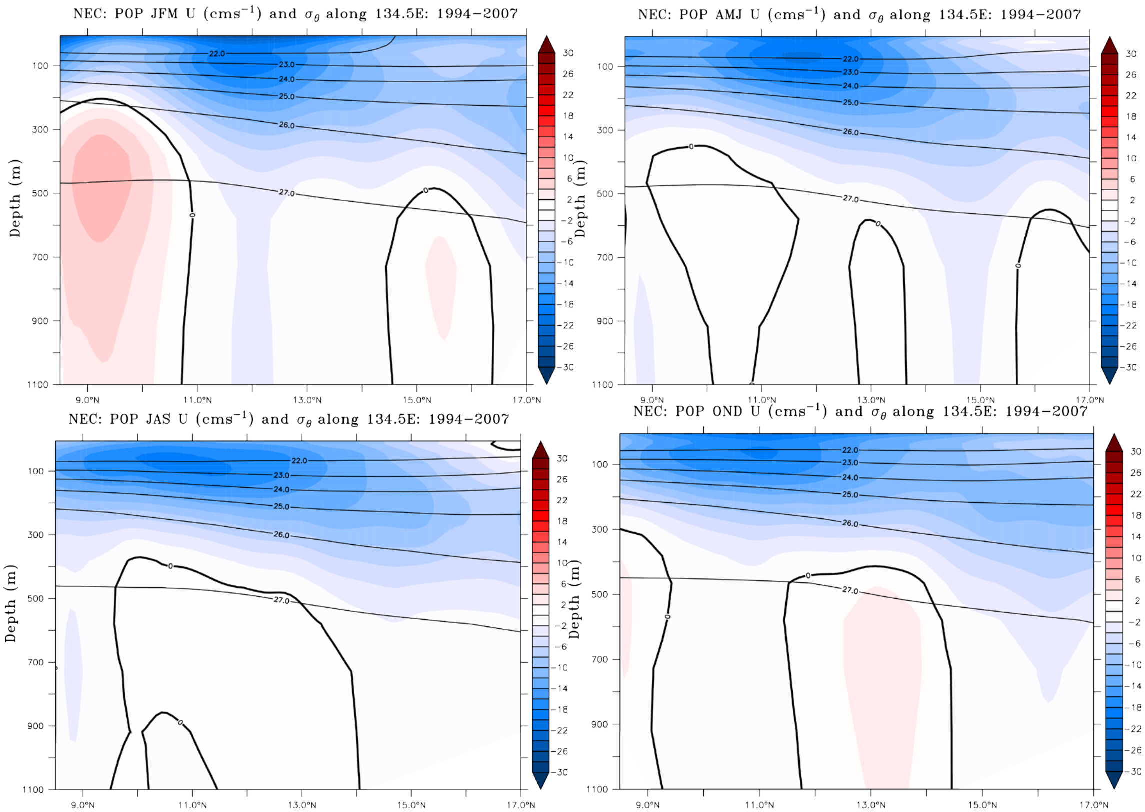

Figure 4. Meridional sections of zonal velocity (cms^{-1}) from POP along 134.5° E between 8.5° and 17°N for winter (Jan-Feb-Mar; upper left), spring (Apr-May-Jun; upper right), summer (July-Aug-Sep; lower left) and fall (Oct-Nov-Dec; lower right). Seasons were constructed from monthly POP climatologies for 1994-2007.